

Time Variable Gravity: An Emerging Frontier in Interdisciplinary Geodesy

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Abstract. The interdisciplinary potential of gravity is stressed with special emphasis on the synergistic use of gravity with other data types. Satellite gravity measurements expected from GRACE and CHAMP will provide unprecedented views of the Earth's gravity field and its changes with time. These measurements will be complementary with those of GOCE, which will provide unprecedented determination of the high-resolution static field. Gravity changes directly reflect changes in the masses of the ocean (thus allowing the separation of steric (heat induced) and non-steric contributions to sea level rise), the Greenland and Antarctic ice sheets, and the water stored in the continents. Not only can measurements of those changes provide a truly global integrated view of the Earth; they have, at the same time, sufficient spatial resolution to aid in the study of individual regions of the Earth. These data should yield information on water cycling previously unobtainable and be useful to both fundamental studies of the hydrologic cycle and practical assessments of water availability and distribution. Together with complementary geophysical data, satellite gravity data represent a new frontier in studies of the Earth and its fluid envelope.

Keywords. Gravitational field, temporal variations of the potential, geodynamics, solid-Earth processes, sea level and glaciology, ocean dynamics, ocean-bottom pressure, hydrology, water storage, and geodetic infrastructure.

1 Introduction and Motivation

The Earth is a dynamic system—it has a fluid, mobile atmosphere and oceans, a continually changing global distribution of ice, snow, and ground water, a fluid core that is undergoing hydromagnetic motion, a mantle both thermally convecting and rebounding from the glacial loading of the last ice age, and mobile tectonic plates. These processes modify the distribution of mass within the

Earth and consequently affect its gravitational field over a wide range of scales in space and time (see Fig. 1). Thus, studies of the Earth's static and temporally varying gravity field can yield not only improved understanding of the Earth's geophysics, but also insight into global change and its impact, and they can contribute to natural hazard mitigation and renewable-resource efforts. These gravitational effects are small fractions of the total field strength, however, so highly accurate measurements are crucial.

Traditionally, the gravity field has been treated as essentially steady state, or "static," over human lifetimes because over 99% of the departure of the field from a rotating fluid figure of the Earth's mass, mean radius, and moment-of-inertia is static in historic time. The static field is dominated by irregularities in the solid Earth caused by convective processes that deform the solid Earth on time scales of thousands to millions of years. Spaceborne gravity measurements have already led to dramatic advances in recent years in the understanding of the structure and dynamics of the core and mantle, the thermal and mechanical structure of the lithosphere, ocean circulation, and plate tectonics. For a review, the reader is referred to Nerem et al. (1995) and NRC (1997) and the references therein. The substantial improvements in the accuracy of static field measurements that would result from the upcoming satellite gravity missions would allow geophysically important smaller-scale features to be resolved and, by improving the geodetic reference frame, would greatly enhance other types of satellite measurements as well.

Nevertheless, it is not in the improved measurement of the static field that we envision the most dramatic advances arising from the next generation of gravity satellites, but in the examination of the remaining less than 1% of the departure of the gravity field, which is caused by processes that vary on timescales ranging from hours to thousands of years. Temporal variations are caused by a variety of phenomena that redistribute mass, including tides raised by the Sun and Moon,

and post-glacial rebound (i.e., creep in the mantle in response to the geologically recent removal of ice sheets). The hydrosphere—oceans, lakes, rivers, ground water—is the source of much of the irregular variations in the time-varying mass distribution from sub-daily (tides) to long-term (aquifer depletion). Variations of mass within the atmosphere are manifested as surface pressure changes and contribute significantly at seasonal and other time scales. The cryosphere—the part of the Earth's surface that is perennially frozen—also has seasonal and interannual variations, as well as a long-term secular effect. Particularly exciting is the potential to study sea level changes, post-glacial rebound, deep circulation of the oceans, and changes in soil moisture and ground and surface water in continental regions. Many of these have application to issues of importance to society such as global change and the availability of natural resources.

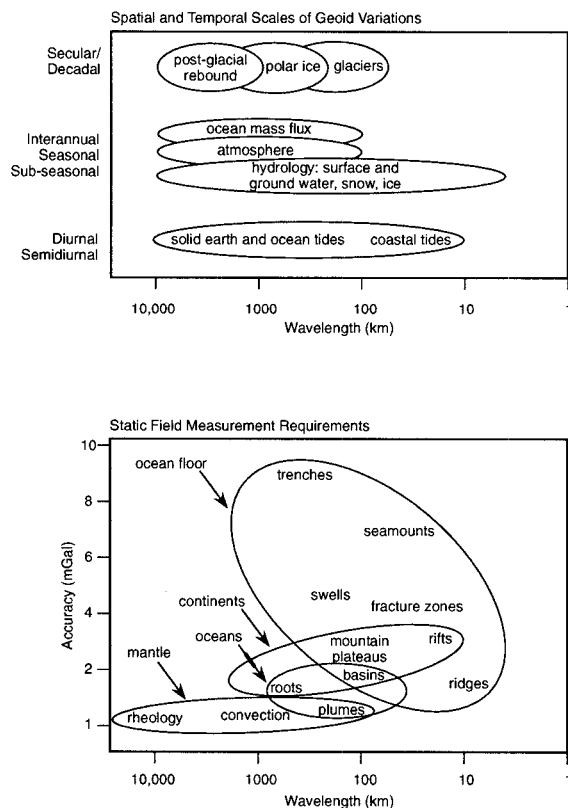


Figure 1. (a) Geophysical phenomena that cause measurable temporal and spatial variations in the Earth's gravity field. Adapted from Bettadpur and Tapley (1996). (b) Summary of requirements for static gravity-measurement accuracy as a function of wavelength, adapted from NASA (1987).

2 Prospects for the Future

Fields of study that would be significantly advanced by improved knowledge of the Earth's gravity field (both static & time varying) include the following:

2.1 Solid-Earth Processes

Improved satellite gravity measurements would constrain properties of mantle convection on scales as small as 200 km (half wavelength, see Fig. 1). An accuracy of $\sim 10^{-2}$ mGal would be met for resolutions larger than 300-400 km, which would permit small, though important, variations in thermal structure to be characterized, thus helping to distinguish between various models of mantle structure. A one-mGal accuracy at length scales of 500-1000 km would resolve discrepant estimates of the depths of continental roots and would also help to distinguish between models of mantle flow. Gravity resolution of approximately 1 mGal over length scales of order ~ 120 km would help constrain the depths of origin of hotspot mantle plumes, which are a major source of intraplate volcanism and enhanced heat flow. Improvements in the application of gravity data to studies of the crust and lithosphere require scales appreciably smaller than 200 km. See NRC (1997) and Dickey et al. (1998).

The recent availability of gravity data from former communist nations will help elucidate interesting geologic structures in remote regions such as the Himalayas and the Tibetan Plateau. Satellite gravity can help to put these data on a unified datum. Satellite gravity data could also be used elsewhere also to calibrate existing terrestrial and marine gravity measurements, improving their continuity across political boundaries and shorelines by several milliGals, which would significantly improve the accuracy of the global terrestrial gravity database.

By detecting the secular change in gravity caused by post-glacial rebound, missions would provide the data needed to resolve differences between models of lower-mantle viscosity and to separate the effects of the rebound from the effects of other processes on sea-level rise, such as changes in ice sheets, groundwater, and surface water. These applications require the highest accuracy at the longest wavelengths. A multi-year mission is essential.

2.2 Sea-Level Rise and Glaciology

The sources of global sea-level rise (between 1.0 and 2.5 mm/yr over the last century) are uncertain; most, but not all, of the likely mechanisms involve

the redistribution of mass from the continents to the ocean. Gravity measurements can help to discriminate between these sources through the continual monitoring of geoid changes, not only on global scales, but also on regional and basin scales. From a satellite-to-satellite tracking (SST) type mission (five-year mission assumed) similar to the GRACE scenario, an increasing mass of water in the ocean equivalent to 0.1 mm/yr of sea level rise can be measured (NRC 1997). Changes in the masses of the Antarctic and Greenland ice sheets are the major unknown contributions to non-steric sea-level rise. Gravity measurements over the ice sheets (particularly in combination with a laser-altimeter mission) would yield a much-improved determination of those contributions (see NRC 1997; Bentley and Wahr 1998; and Dickey et al. 1998).

Satellite gravity measurements are capable of yielding valuable information about the mass balance of individual drainage systems within the Antarctic ice sheet, as well as of the ice sheet as a whole. Glaciologists could use such information to test models of ice dynamics, which are essential to the prediction of future sea-level change. Satellite gravity could also be used to study secular, interannual, and seasonal changes in the mass of ice and snow in regions characterized by a large number of glaciers and ice caps. A prime example is the glacier system that runs from the Kenai Peninsula in southern Alaska down to the coastal ranges of the Yukon and British Columbia.

Accurate evaluation of post-glacial rebound models, together with improved ocean circulation models, should remove significant errors from old tide-gauge records, thus permitting improved estimates of sea level rise during the past century.

2.3 Ocean Dynamics

Surface currents can be estimated from the horizontal surface pressure gradient, which is proportional to the departure of the sea surface elevation from the marine geoid. The accuracy of ocean heights measured by satellite altimetry is presently approaching ~10 mm. Nevertheless, present geoid slope errors are much larger at resolutions shorter than about 3000 km, which prevents the accurate measurement of absolute surface pressure gradients at those scales (see Fig. 2). A satellite gravity measurement can eliminate the geoid uncertainty in horizontal pressure gradients at much shorter scales (to about 300 km—see NRC 1997 and Dickey et al. 1998). It would also allow recomputation of accurate altimetric orbits for past

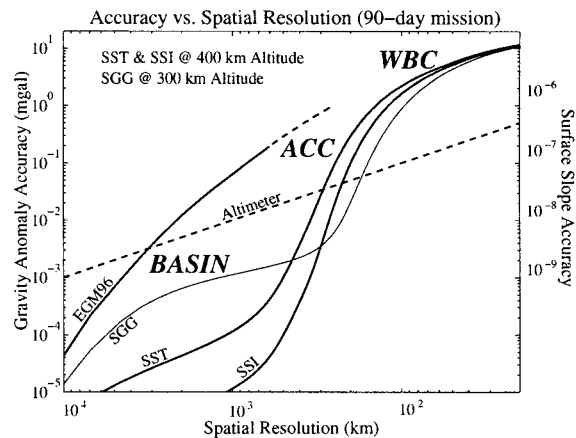


Figure 2. (from Dickey et al. 1998). Errors versus spatial resolution for the Spaceborne Gravity Gradiometry (SGG) 300-km mission, the Low-Low Satellite-to-Satellite Microwave Tracking (SST) and the Low-Low Satellite-to-Satellite Laser Interferometry (SSI) 400-km missions, and the EGM96 gravity model. The surface-slope scale is shown on the right-hand axis and the approximate slope magnitude and spatial scales of basin-wide currents (BASIN), the Antarctic Circumpolar Current (ACC) and Western Boundary Currents (WBC) are indicated. The dashed line indicates the slope error versus separation distance assuming a 10-mm uncertainty in altimeter height differences. The payoff for the static ocean problem appears to be in the range of about 300 to 3000 km where the gravity error is dominant without a gravity mission and becomes insignificant with a gravity mission.

satellites, back to 1985, improving studies of long, global sea-level time series. Studies in ocean regions with a strong barotropic component will benefit from knowledge gained from the static geoid. These include the recirculation cells in the subtropical gyres of the western Atlantic, the Kuroshio Current, the Agulhas Current, and the Antarctic Circumpolar Current.

Most of what is known about the ocean occurs in the upper 500 meters. Studies suggest that uncertainties in the deep circulation and heat and mass transport will be reduced by a factor of two or more in oceanographic regions that are currently data sparse. Part of this reduction comes from an improvement in estimates of surface currents. For example, the geostrophic advective terms in the mixed-layer heat budget would be resolvable with an uncertainty of less than 10 W m^{-2} on length scales longer than 300 km.

The combination of altimetry and time-varying gravity will allow the separation of the steric and mass components of sea-level rise variations, including secular change. This separation will substantially increase the usefulness of sea-level

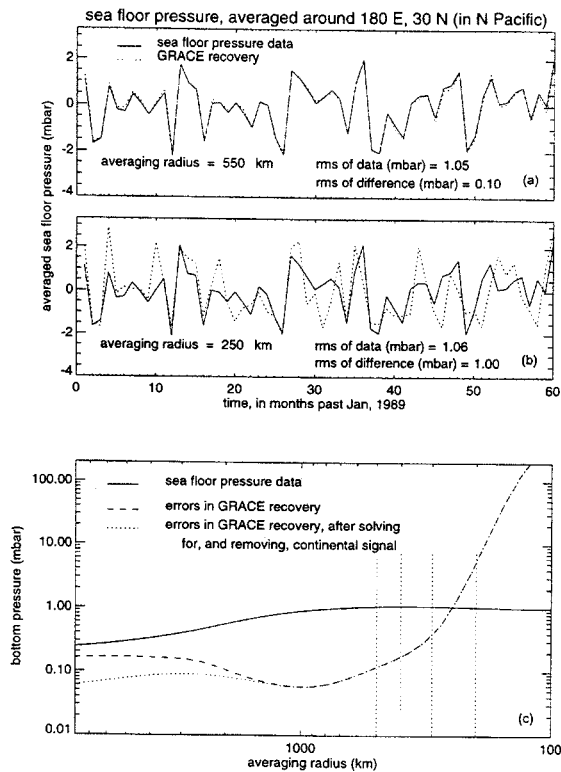


Figure 3 (from Wahr et al. 1998). The results of simulations in which synthetic GRACE data are used to recover the seafloor pressure at a location in the middle of the North Pacific Ocean (180°E , 30°N). Panels (a) and (b) show five years of monthly values for two averaging radii. The solid line is the signal that went into the simulation, and the dotted line is the signal inferred from the synthetic GRACE data. Panel (c) shows the rms of five years of monthly data as a function of averaging radius. The solid line is the estimate from the data. The dashed line represents the accuracy of the GRACE results, after solving for, and removing, the continental contributions.

measurements in testing ocean models and constraining ocean circulation.

Interesting and detectable signals that indicate changes in sea-floor pressure averaged over spatial scales of a few hundred kilometers and larger are expected. These will allow the detection of large-scale abyssal ocean current variations with seasonal to interannual time scales (see Fig.3). Detection of these phenomena requires a multi-year mission lifetime and high accuracies at long wavelengths.

2.4 Continental Water Variation

Gravity missions can provide estimates of changes in water storage over spatial scales of several hundred kilometers and larger that would be accurate to 10 mm or better (NRC 1997 and Wahr

et al. 1998, see Fig. 4). These would benefit the Global Energy and Water Cycle Experiment (GEWEX) directly and would be useful to hydrologists for connecting hydrological processes at traditional length scales (tens of kilometers and less) to those at longer scales. Natural and human induced variations in soil moisture, groundwater level and snowpack can be expected to be detected. Improved knowledge of soil moisture would enhance estimates of agricultural productivity by helping to assess water available for irrigation. Water storage is important also to meteorologists because of the effect of soil moisture on evapotranspiration.

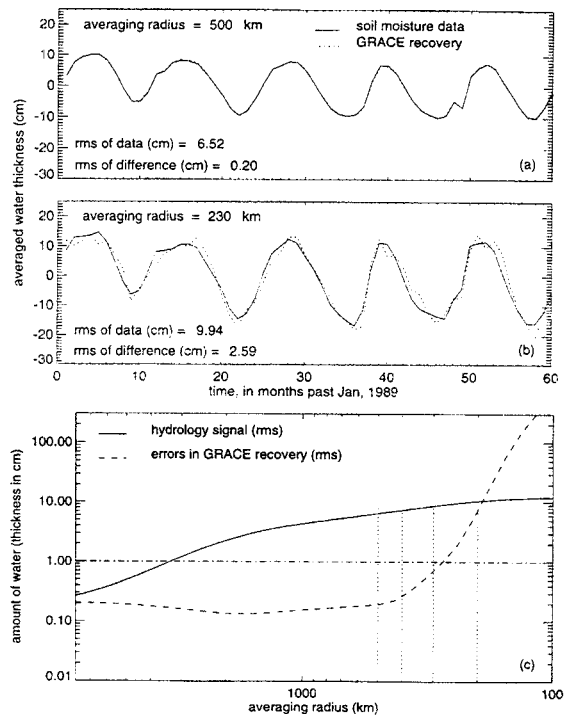


Figure 4 (from Wahr et al. 1998). The results of simulations in which synthetic GRACE data are used to recover the hydrological signal at Manaus, Brazil (in the Amazon River Basin). The simulated geoid data include the GRACE geoid errors, as well as contributions from hydrology and oceanography, and our estimated errors in the atmospheric pressure data. Panels (a) and (b) show five years of monthly values for two averaging radii. The solid line is the hydrology signal that went into the simulation, and the dotted line is the signal inferred from the synthetic GRACE data. Panel (c) shows the rms of five years of monthly data as a function of averaging radius. The solid line is the estimate from the hydrology data. The dashed line represents the accuracy of the GRACE results, estimated as the rms of the difference between the GRACE recovered values and the hydrology signal.

Both monitoring and prediction are technologically feasible and hold promise for the mitigation of natural hazards and ongoing evaluation of the state of one of the world's most important renewable resources, its fresh water. Measurements of gravity variations can help monitor aquifer depletion. Gravity results can aid in monitoring snow pack, predicting floods and the runoff available for irrigation, and assessing agricultural productivity on large scales.

2.5 The Dynamic Atmosphere

The atmosphere is currently the best-measured fluid of any the Earth's subsystems. Its effects on time-variable gravity can be largely removed from the satellite data, given accurate enough global surface atmospheric pressure data. This fact is key in unraveling the effects of the other subsystems (such as the hydrological cycle and the mass balance of the Antarctic ice sheet) involved in gravity variations. With increasing accuracy in gravity measurement, precise knowledge of the uncertainty in atmospheric surface pressure on seasonal, annual, and secular timescales becomes increasingly important.

Reliable, extended-range forecasting, which would require interactive coupling between the atmosphere and the water in soils and the ocean, would benefit from hydrological constraints and improved understanding of ocean dynamics.

Gravity measurements with high temporal and spatial resolutions may improve the atmospheric databases and aid in the verification of models in areas where atmospheric measurements are lacking. However, it would be much more effective to have a global network of barometers sufficient to remove the atmospheric signals from the gravity data (see NRC 1997 and Dickey et al. 1998).

2.6 A Tool for Science

Various mission scenarios offer significant improvements in the static gravity field that are useful for several additional important applications. These include: an improved reference frame for defining position coordinates; better calculation of orbits for other remote-sensing applications, such as altimetry and SAR (synthetic aperture radar) interferometry; and a more accurate geoid, the equipotential surface to which land elevations ideally refer and to which ocean circulation is referred (see NRC 1997 and Dickey et al. 1998).

3 Summary

As shown in the examples above, satellite gravity measurements can provide unprecedented views of the Earth's gravity field and, given sufficient duration, its changes with time. Not only can they provide a truly global integrated view of the Earth, they have, at the same time, sufficient spatial resolution to aid in the study of individual regions of the Earth. Together with complementary geophysical data, satellite gravity data represent a new frontier in studies of the Earth and its fluid envelope.

Acknowledgements. The author gratefully acknowledges the other members of the National Research Committee, Earth's Gravity from Space: Charles R. Bentley, Roger Bilham, James A. Carton, Richard J. Eanes, Thomas A. Herring, William M. Kaula, Gary S.E. Lagerloef, Stuart Rojstaczer, Walter H.F. Smith, Hugo M. van den Dool, John M. Wahr, and Maria T. Zuber. The work of this committee formed the basis for this paper. The work described in this paper was performed by the author at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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